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Impacts of White Pine Blister Rust in 22 Plantations of Western White Pine in Northern Idaho: 1995-2011

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ABSTRACT

*The impacts of white pine blister rust (*Cronartium ribicola*) were monitored for 16 years in 22 plantations of western white pine (*Pinus monticola*) in northern Idaho. Monitoring started in 1995 when plantations were 1-11 years old with remeasurements in 2000, 2006, and 2011. The results show that F_2 stock is outperforming both F_1 and natural regeneration. Incidence of white pine blister rust within individual plantations varied from 6% to 86% and averaged almost 50% in 2011. Infection in 16 of 20 F_2 plantations was above 34%; three plantations had incidence less than 10%. After 16 years, mortality tends to be about half the cumulative infection level but varied widely from 0 to 63% with an average of about 25%. Average annual infection and mortality rates were also variable and are not well-correlated with hazard rating estimates derived from site variables. Although the few plantations with low levels of infection after 15 years tended to remain low, changes in incidence and mortality in most plantations did not follow any consistent trend over this time interval, thus making it difficult to predict future impacts.*

INTRODUCTION

Western white pine (*Pinus monticola*) was once a dominant tree species on more than five million acres of the moist, mid-elevation, mixed-conifer forests of the Inland Northwest. Today, western white pine is a significant stand component on less than five percent of this area (Fins et al. 2001, Harvey et al. 2008, Neuenschwander et al. 1999). This dramatic reduction was caused

primarily by the introduction of *Cronartium ribicola*, the fungal pathogen that causes white pine blister rust (WPBR), but was exacerbated by selective harvesting of western white pine, fire suppression activities that greatly reduced the number and size of fires that had historically provided ideal sites for western white pine regeneration, and mortality caused by mountain pine beetle (*Dendroctonus ponderosae*). Mountain pine beetle has always been an important pest of mature western white pine, but losses were historically offset by the beneficial effects of mixed-severity and stand-replacing fires that provided sites for natural regeneration. WPBR, however, causes substantial mortality in western white pine seedlings and saplings, thus greatly limiting regeneration in the forests western white pine once dominated (Smith and Fischer 1997).

As a result of these impacts, western white pine declined across much of its native range in the Inland Northwest, altering species composition and successional processes such that shade-tolerant species became much more dominant. Currently the Douglas-fir (*Pseudotsuga menziesii*) cover type is almost double its historic acreage, and the grand fir (*Abies grandis*) / western hemlock (*Tsuga heterophylla*) cover type has increased in area five times (Samman et al. 2003). This increase in the more shade-tolerant species, which are often more susceptible to native pathogens and insects, has resulted in a loss of ecosystem function and diversity (Byler and Hagle 2000, Harvey et al. 2008, Samman et al. 2003).

Cronartium ribicola was introduced into the Pacific Northwest from Europe around 1910 and expanded rapidly throughout the range of western white pine; the first infection of pine in northern Idaho is thought to have occurred by 1923 (Lachmund 1926, Mielke 1943, Maloy 1997). *Cronartium ribicola* has a complex life cycle that requires an alternate host, primarily *Ribes* species, to produce spores that infect five-needled pines through their foliage. By the 1940s, enough was thought to be known about the relationships between western white pine regeneration, *Ribes* ecology, and timber harvest to develop an integrated program of *Ribes* suppression and western white pine regeneration on USDA Forest Service (USFS) land (Matthews and Hutchison 1948, Moss and Wellner 1953). By the mid-1960s, however, it had become obvious to forest managers that the *Ribes* eradication program and other disease-control efforts were not succeeding. The USFS western white pine management policy was revised in 1965; planting was discontinued and management of other species was emphasized (Ketcham et al. 1968).

The USFS initiated a rust-resistance breeding program in 1950 based on the apparent existence of low levels of natural resistance to WPBR in western white pine (Bingham et al. 1953, Bingham 1983). Rust-free western white pines that had survived years of exposure in severely-infected natural stands were identified. Seed produced from controlled crosses of these rust-free individuals were grown and exposed to *C. ribicola* spores in the nursery to determine which parents possessed resistance and which did not. Grafts of the best-performing parent trees were then established in a seed orchard to produce first generation (F_1) seed (Bingham et al. 1963).

Progeny from F_1 seed were tested further in inoculation trials and used to establish seed orchards of F_1 trees that would cross-pollinate and produce second generation (F_2) seed.

Resistance levels in F_1 ranged from 20-30% following either inoculations and (or) out-planting (e.g. - Steinhoff 1971, Bingham et al. 1973). Initial expectations for F_2 performance, based on known F_1 performance and the expected genetic gain from F_1 to F_2, was that F_2 resistance would be around 50% (Bingham 1983). However, a nursery-based inoculation test indicated that 66% of F_2 western white pine seedlings remained uninfected 2.5 years after artificial inoculation (Hoff et al. 1973). Based on this single test, F_2 stock became known as "rust resistant" and the notion that F_2 stock would remain 66% canker-free throughout its life was unfortunately extrapolated directly to operational plantations without the benefit of field-based "realized gains" trials (Lupo 2004, Mahalovich 2010).

As F_2 seedlings became available in the late 1970s, western white pine planting increased significantly on federal, state, and private forest lands in the Inland Northwest. By the late 1980s, anecdotal evidence and monitoring of operational plantations revealed that on some sites WPBR infection of F_2 stock exceeded expected levels (Fins et al. 2001, Muller 2002, Schwandt and Ferguson 2003, Kearns et al. 2012). Western white pine at some sites were relatively rust-free while on other sites over 90% were infected. This monitoring project was established to document the impacts of WPBR in operational plantations of improved western white pine, including F_1 and F_2 rust-resistant stock as well as natural regeneration, over time (Mathiasen and Schwandt 1993).

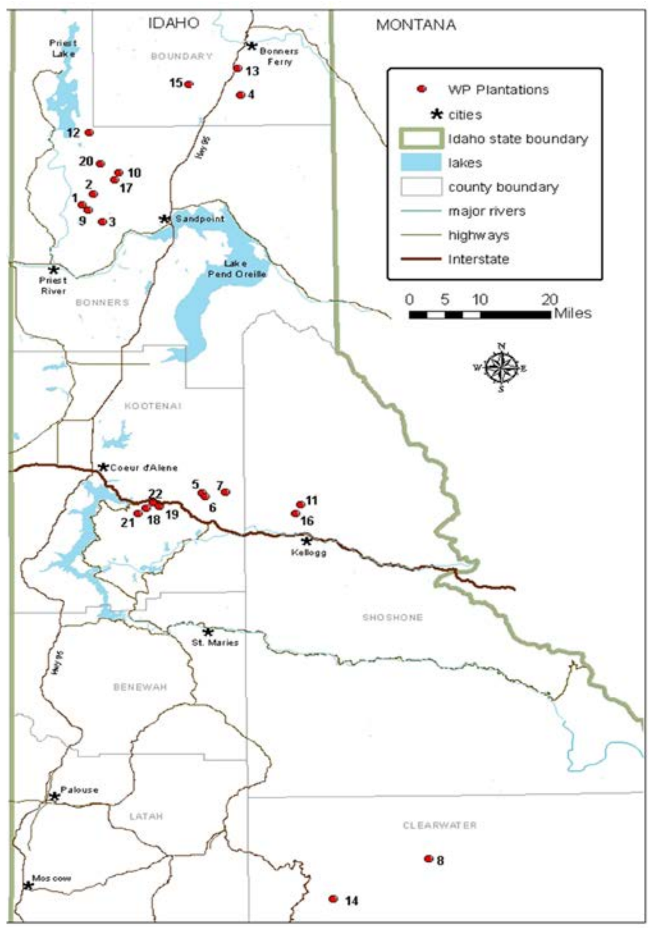

Figure 1. Locations of monitored western white pine plantations.

METHODS

Monitoring plots were established in 22 USFS and Idaho Department of Lands (IDL) western white pine plantations between 1991 and 2000 (Table 1). Seven plantations were located on USFS lands and 15 on IDL lands. All sites were planted with western white pine seedlings with

improved rust resistance. Twenty of the sites were planted with F_2 stock grown from seed produced at the Bingham Seed Orchard in Moscow, Idaho. The other two sites were planted with F_1 western white pine grown from seed produced in the Sandpoint Seed Orchard. The plantations are all located in northern Idaho between Orofino and the Canadian border (Figure 1).

Table 1. Summary of 22 monitored western white pine plantations.

#[1]	Plantation	Ownership[2]	Year Planted	Year Plots Established	WP Stock Type	Planted White Pine	Natural White Pine
1	All the Way	IDL	1984	1991	F2	95	1
2	Big Foxy	IDL	1993	1995	F2	103	1
3	Blue Creek	IDL	1993	1995	F2	99	0
4	Contrary Creek	IDL	1993	1993	F2	89	13
5	Copper-Gimlet 1	USFS	1986	1992	F2	174	29
6	Copper-Gimlet 2	USFS	1986	1992	F2	61	16
7	Copper-Gimlet 21	USFS	1984	1992	F2	164	116
8	East Thunder	IDL	1994	2000	F2	126	1
9	Happy Blue	IDL	1993	1995	F2	98	0
10	Keokee Creek	IDL	1985	1993	F2	223	4
11	Lost Cat	IDL	1993	1995	F2	112	0
12	Lost Jungle	IDL	1993	1995	F2	77	2
13	Paradise Valley	IDL	1985	1991	F2	111	2
14	Pick & Pan Creek	IDL	1994	2000	F2	73	1
15	POL 92 - A	IDL	1992	1993	F2	88	88
16	Remas	IDL	1994	1995	F2	99	5
17	Uleda Creek	IDL	1992	1995	F2	114	0
18	Varnum 11	USFS	1989	1992	F2	106	12
21	Varnum 23b	USFS	1988	1992	F2	111	57
22	Waters Creek	IDL	1985	1995	F2	136	3
19	Varnum 2	USFS	1988	1992	F1	116	107
20	Varnum 23a	USFS	1988	1992	F1	129	28

[1] Refers to plantation number on map (Figure 1)
[2] IDL = Idaho Department of Lands, USFS = U.S.Forest Service

The original study plan described plantation selection, plot establishment procedures and initial data collection (Mathiasen and Schwandt 1993). The study consists of 0.05-acre circular plots spaced two to six chains apart along transects through the plantations. Plot centers were staked and all western white pine within the plot were tagged. Initial data recorded included tree height, age, seedling source (planted or natural), condition (live or dead), WPBR severity (count of cankers and percent bole girdle), and other damage agents. *Ribes* species and density were also recorded on each plot. Where possible, a minimum of 100 western white pine seedlings were

tagged per plantation, but the number of monitored trees per plantation varied from 61 to 223 (Table 1).

White pine blister rust infections start by spore infection of needles that then grows into the branch or bole where a distinct canker develops over several years. To be consistent and minimize canker recognition issues, WPBR infection was recorded the year at least one identifiable canker was observed anywhere on a tree. Root disease symptoms and mechanical damage can be confused with WPBR infections at the base of trees (Molnar and McMinn 1960), particularly on F_2 stock that may possess resistance mechanisms that can cause abnormal canker development (Eckert 2007). Therefore, trees with questionable basal WPBR infections were noted so they could be carefully re-examined during subsequent remeasurements. Periodic monitoring proved invaluable as it allowed us to confirm presence or absence of WPBR as canker diagnosis became more obvious over time. Once a tree was diagnosed with a WPBR canker it was categorized as infected from that point on unless subsequent observations proved the initial diagnosis to be inaccurate. Incidence of WPBR across remeasurement periods is therefore a cumulative measure of the infection level. Dead trees were carefully examined for primary cause of death, but in a few cases where we could not confidently assign a cause, mortality was categorized as unknown.

Figure 2. Copper-Gimlet 2 F_2 plantation in 2002 with WPBR incidence of 45%.

The initial plan called for the remeasurement of the plots on three- to five-year intervals (Figure 2). Kearns et al. (2012) reported results from the first 11 years of monitoring of 20 plantations from 1995 through 2006. Data presented here cover 16 years and include measurements completed in 1995, 2000, 2006, and 2011. Also included here are two plantations, East Thunder and Pick & Pan Creek, which were installed in 2000 but not included in the previous report. Data collected in the 2011 remeasurement included *Ribes* species and density, tree diameter, condition, WPBR severity, canker count, and percent of stem canker girdling.

Incidence is the proportion of trees infected and is presented in this report as both the total percent infection of the stock type (e.g. - see Table 2, orange-colored highlight) and as the

average of the infection levels of all the plantations containing that stock type (e.g. - see Table 2, blue-colored highlight). The actual average annual infection rate (aAIR) was calculated for each plantation by dividing WPBR incidence by the plantation's age in 2011. An estimated annual infection rate (eAIR) was calculated using a formula developed by Muller (2002). Annual rate of new infections for each measurement period was calculated by dividing the change in incidence between measurements by the number years in the measurement period. Severity of WPBR was based on number and location of cankers. WPBR cankers were categorized as lethal if they occurred on the bole or on a branch within six inches of the bole. Infected trees that had branch cankers between six and 24 inches from the bole and less than eight feet from the ground were classified as prunable. WPBR branch cankers more than 24 inches from the bole were classified as safe (Schwandt et al. 2013b), but the tree was categorized as infected.

RESULTS and DISCUSSION

The following results are based on data from nearly 3,000 western white pine: 2,259 F_2 stock; 245 F_1 stock; and 466 naturally regenerated western white pine ("naturals"), 331 in F_2 plantations and 135 in F_1 plantations, that seeded into the plantations (Table 1).

Incidence of White Pine Blister Rust

Overall, infection levels for the F_2 stock were lower than those of both F_1 stock and natural regeneration. Data from the 1995 measurement show that infection levels varied from 0 to 49% for the F_2 stock (Table 2). Nine of the 18 F_2 plantations monitored in 1995 were less than five years old and had no WPBR cankers observed. In 1995, 13.7% of the 2,060 F_2 trees were infected with WPBR, and the average infection level of the F_2 plantations was 9.8%. In the seven F_2 plantations where 10 or more naturals were monitored, WPBR incidence in the F_2 averaged 13.2% while the naturals averaged 13.7% (Table 2, Figure 3). Since all but one of these plantations were burned during slash management and/or site preparation activities, it is assumed that most, if not all, the natural regeneration started from seed at or around the time the sites were planted with 1- or 2-year-old seedlings, and were therefore exposed to *C. ribicola* spores for similar time frames.

Five years later, in 2000, average incidence of WPBR in the 20 F_2 plantations had more than doubled to 25.4%; 28.6% of all F_2 stock were infected (Table 2). Average WPBR incidence of the natural western white pine in the seven plantations nearly quadrupled to 54.4% over the same period (Figure 3). By 2006, 41.1% of the F_2 stock was infected, and the average F_2 plantation infection level had increased to 37.6% while the average infection level in the naturals increased to 62%.

Table 2. Cumulative white pine blister rust infection and mortality by stock type and measurement date; sorted by 2011 infection level.

Plantation/Stock	Age in 1995	N	Cumulative Rust Infection (%) 1995	2000	2006	2011	Average Annual Infection[2]	Cumulative Rust Mortaity (%) 1995	2000	2006	2011	Average Annual Mortality
F_2												
All the Way	11	95	0.0	0.0	5.3	6.3	0.23	0.0	0.0	0.0	0.0	0.00
Paradise Valley	10	111	0.9	0.9	4.5	6.3	0.24	0.9	0.9	0.9	0.9	0.03
Contrary Creek	2	89	0.0	0.0	0.0	9.0	0.50	0.0	0.0	0.0	0.0	0.00
Big Foxy	2	103	0.0	7.8	26.2	32.0	1.78	0.0	1.9	12.6	16.5	0.92
Lost Jungle	2	77	0.0	14.3	26.0	35.1	1.95	0.0	0.0	15.6	19.5	1.08
POL 92 - A	3	88	0.0	8.0	22.7	36.4	1.92	0.0	1.1	4.5	6.8	0.36
Blue Creek	2	99	0.0	7.1	25.3	41.4	2.30	0.0	1.0	8.1	12.1	0.67
Varnum 11	6	106	1.9	23.6	29.2	50.0	2.27	0.9	3.8	9.4	18.9	0.86
Pick & Pan Creek	1	73	na	11.0	19.2	50.7	2.98	na	0.0	2.7	11.0	0.65
Copper-Gimlet 21	11	164	35.4	45.7	47.0	51.2	1.90	17.1	31.1	34.8	39.0	1.44
Lost Cat	2	112	0.0	23.2	42.0	51.8	2.88	0.0	7.1	25.0	31.3	1.74
Happy Blue	2	98	0.0	29.6	42.9	52.0	2.89	0.0	17.3	27.6	32.7	1.82
Copper-Gimlet 2	9	61	13.1	45.9	45.9	55.7	2.23	9.8	16.4	18.0	18.0	0.72
Uleda Creek	3	114	0.0	11.4	29.8	57.0	3.00	0.0	0.9	7.9	16.7	0.88
Keokee Creek	10	223	33.6	40.4	48.4	60.5	2.33	25.1	30.9	33.6	37.2	1.43
Remas	1	99	0.0	29.3	53.5	61.6	3.62	0.0	17.2	27.3	28.3	1.66
Varnum 23b	7	111	2.7	40.5	51.4	70.3	3.06	0.9	11.7	33.3	36.0	1.57
Copper-Gimlet 1	9	174	39.1	49.4	67.8	81.0	3.24	14.9	30.5	37.9	39.7	1.59
Waters Creek	10	136	49.3	75.7	83.8	83.8	3.22	31.6	43.4	55.1	63.2	2.43
East Thunder	1	126	na	43.7	81.7	86.5	5.09	na	2.4	20.6	38.9	2.29
Total/Overall percent[3]		2259	13.7	28.6	41.1	52.0		7.9	13.7	21.6	26.3	
Plantation Average		113	9.8	25.4	37.6	48.9	2.38	5.6	10.9	18.7	23.3	1.11
Change from Previous Year				15.6	12.3	11.3			5.3	7.9	4.6	
Natural in F_2[1]												
Contrary Creek	2	13	0.0	0.0	0.0	7.7	0.43	0.0	0.0	0.0	0.0	0.00
Varnum 23b	7	57	3.5	64.9	64.9	68.4	2.97	3.5	38.6	49.1	49.1	2.14
POL 92 - A	3	88	0.0	29.5	56.8	73.9	3.89	0.0	9.1	21.6	27.3	1.44
Varnum 11	6	12	0.0	66.7	75.0	75.0	3.41	0.0	8.3	50.0	50.0	2.27
Copper-Gimlet 21	11	116	17.2	59.5	67.2	75.9	2.81	7.8	44.8	50.9	55.2	2.04
Copper-Gimlet 1	9	29	37.9	72.4	82.8	86.2	3.45	17.2	27.6	62.1	65.5	2.62
Copper-Gimlet 2	9	16	37.5	87.5	87.5	87.5	3.50	37.5	75.0	87.5	87.5	3.50
Total/Overall percent		331	11.8	52.9	64.0	72.8		6.7	31.1	43.5	46.8	
Plantation Average		47	13.7	54.4	62.0	67.8	2.92	9.4	29.1	45.9	47.8	2.00
Change from Previous Year				40.7	7.6	5.8			19.7	16.8	1.9	
F_1												
Varnum 23a	7	129	56.6	84.5	91.5	92.2	4.01	31.8	48.1	69.8	75.2	3.27
Varnum 2	7	116	63.8	84.5	88.8	97.4	4.23	20.7	69.0	75.0	75.9	3.30
Total/Overall percent		245	60.0	84.5	90.2	94.7		26.5	58.0	72.2	75.5	
Plantation Average		123	60.2	84.5	90.1	94.8	4.12	26.2	58.5	72.4	75.5	3.28
Change from Previous Year				24.3	5.7	4.7			32.3	13.9	3.1	
Natural in F_1[1]												
Varnum 2	7	107	83.2	95.3	95.3	96.3	4.19	41.1	92.5	94.4	94.4	4.10
Varnum 23a	7	28	17.9	92.9	96.4	96.4	4.19	10.7	78.6	89.3	92.9	4.04
Total/Overall percent		135	69.6	94.8	95.6	96.3		34.8	89.6	93.3	94.1	
Plantation Average		68	50.5	94.1	95.9	96.3	4.19	25.9	85.6	91.8	93.6	4.07
Change from Previous Year				43.6	1.8	0.4			59.7	6.2	1.8	

[1] Plantations with 10 or more natural western white pine. [2] Actual average annual rate (aAIR) from planting date through 2011.

[3] Highlighted cells refer to descriptions provided in the text.

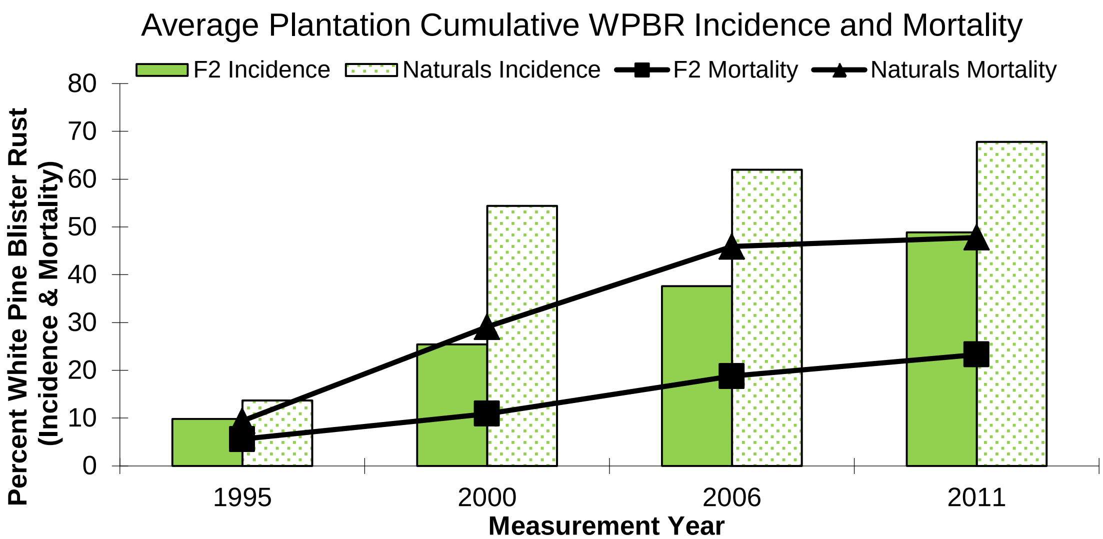

Figure 3. Average cumulative percent incidence and mortality in F_2 and natural regeneration in F_2 plantations from 1995 to 2012.

By 2011, after 16 years of monitoring, all 20 F_2 plantations had some level of WPBR; only four had incidence below the 34% maximum expected level projected from the early WPBR screening trials (Hoff et al. 1973). The overall infection level of all sampled F_2 stock was 52.0%, while 72.8% of the naturals were infected (Table 2). The plantation average infection levels ofthe 20 F_2 plantations was nearly 49% for F_2 and varied from 6.3 to 86.5%. The average infection level of the naturals in the seven F_2 plantations with natural regeneration had increased to 67.8%, varying from 7.7 to 87.5%; while the average infection level on the F_2 stock in the same seven plantations was 50.5% (range 9.0 to 81.0%).

Only two plantations of F_1 stock, with a total of 245 F_1 western white pines, were monitored (Tables 1 and 2). Average WPBR incidence increased from 60.2% of F_1 stock in 1995 to 94.8% in 2011. The average WPBR infection level of natural regeneration within these two plantations was 50.5% in 1995, increased to nearly 94.1% infection in the next five years, and was 96.3% in 2011.

The average annual rate of newly infected western white pines varied between plantations and measurement intervals (Table 3). In the interval from 1995–2000, the average rate of newly infected F_2 stock was 3.1% and ranged from 0–7.6%. During the next two monitoring periods, this rate declined to 2.0 and 2.3, respectively, with a range from 0.0 to 6.3%. Over the entire 16-year monitoring period the average annual rate of increase of newly-infected F_2 stock was 2.3% with a range of 0.3–4.2%. The natural regeneration in the seven F_2 plantations where it was monitored had an average annual rate of new infections of 8.1% during the 1995–2000 period but averaged 3.4% annually over the 16 year monitoring period (range 0.5–4.7%).

Table 3. Average annual rate of increase in white pine blister rust infected western white pines by measurement period.

	Average annual rate (%) of new infections by measurement interval							
	Planted				Natural [1]			
Plantation/Stock	95 - 00	00 - 06	06 - 11	95 - 11	95 - 00	00 - 06	06 - 11	95 - 11
F2								
Paradise Valley	0.0	0.6	0.4	0.3	---	---	---	---
All the Way	0.0	0.9	0.2	0.4	---	---	---	---
Contrary Creek	0.0	0.0	1.8	0.6	0.0	0.0	1.5	0.5
Copper-Gimlet 21	2.1	0.2	0.9	1.0	8.4	1.3	1.7	3.7
Keokee Creek	1.3	1.3	2.4	1.7	---	---	---	---
Big Foxy	1.6	3.1	1.2	2.0	---	---	---	---
Lost Jungle	2.9	1.9	1.8	2.2	---	---	---	---
Waters Creek	5.3	1.3	0.0	2.2	---	---	---	---
POL 92 - A	1.6	2.5	2.7	2.3	5.9	4.5	3.4	4.6
Blue Creek	1.4	3.0	3.2	2.6	---	---	---	---
Copper-Gimlet 1	2.1	3.1	2.6	2.6	6.9	1.7	0.7	3.0
Copper-Gimlet 2	6.6	0.0	2.0	2.7	10.0	0.0	0.0	3.1
Varnum 11	4.3	0.9	4.2	3.0	13.3	1.4	0.0	4.7
Lost Cat	4.6	3.1	2.0	3.2	---	---	---	---
Happy Blue	5.9	2.2	1.8	3.3	---	---	---	---
Uleda Creek	2.3	3.1	5.4	3.6	---	---	---	---
Remas	5.9	4.0	1.6	3.9	---	---	---	---
Varnum 23b	7.6	1.8	3.8	4.2	12.3	0.0	0.7	4.1
East Thunder	na	6.3	1.0	na	---	---	---	---
Pick & Pan	na	1.4	6.3	na	---	---	---	---
Average	3.1	2.0	2.3	2.3	8.1	1.3	1.2	3.4

[1] Sites with 10 or more natural white pine

Since the plantations in this study were 1-11 years old when measured in 1995, data on WPBR incidence and mortality span plantation ages from 1 to 27 years (Table 2). The length of exposure to *C. ribicola* spores will likely influence incidence of WPBR, and older plantations may have higher infection levels as a result. To examine this relationship, plantations were grouped into age classes. When grouped by plantation age, we found that the greatest increases in WPBR incidence in the F_2 stock occurred before age 19–23 after which the rate declined (Figure 4, Table 4). Of the 11 F_2 plantations in the 19–23 year age class, incidence of WPBR averaged 46.9%, a 6.3% increase over the 14–18 age class (Table 4). The cumulative WPBR infection level of the seven F_2 plantations in the 25–27 age class was 49.2% an increase of only 2.3% over the average of the 19–23 year age class. The rate of increase in WPBR incidence also declined with plantation age in both the F_1 and natural stock.

Individual plantations generally showed no consistent trends in infection levels over time (Figure 5). For example, some plantations (i.e. Copper-Gimlet 21 and Keokee Creek) had relatively high

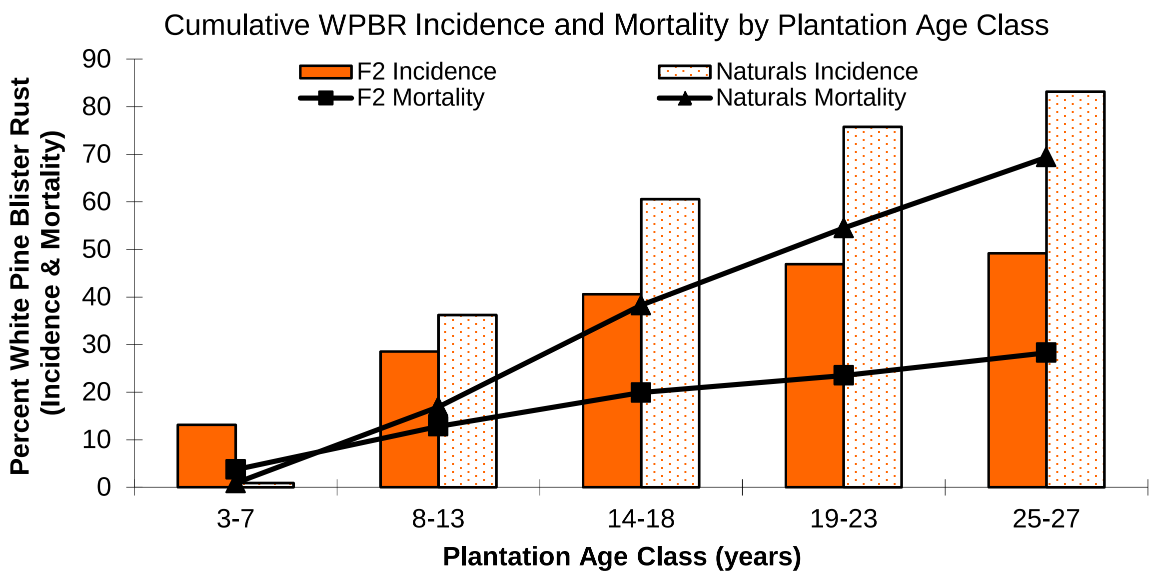

Figure 4. Cumulative WPBR incidence and mortality by stock type and age class

infection levels when measured in 1995 (35.4 and 33.6%, respectively), but incidence did not increase as much as other plantations over the next 16 years. Incidence of WPBR in other plantations (i.e. - Varnum 23b and Varnum 11) was relatively low in 1995, 2.7 and 1.9%, respectively, but increased rapidly over the 16-year monitoring period. The only exceptions were Paradise Valley and All the Way, which consistently had infection levels less than 10%. This general lack of pattern across plantations makes future predictions regarding infection levels based on incidence in a given year or plantation age impractical (see "*Site Factors and Hazard Rating*" below).

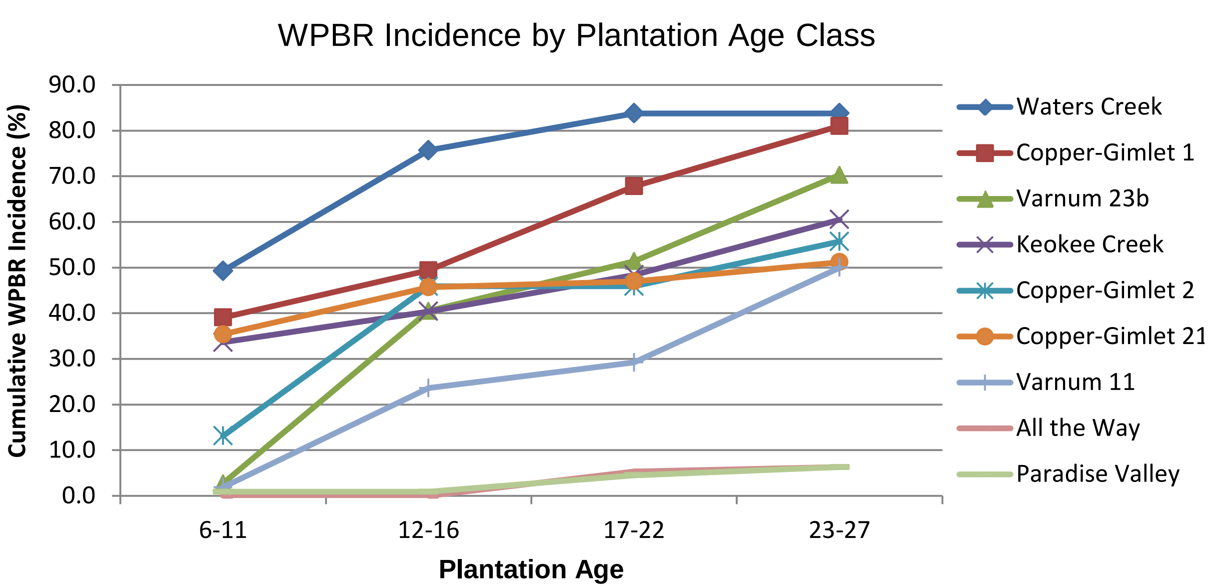

Figure 5. Changes in incidence of WPBR in the nine oldest F_2 plantations over time.

Table 4. Cumulative white pine blister rust infection and mortality for resistant planting stock and natural regeneration by plantation age class.

Plantation/Stock	Age in 1995	3-7	8-13	14-18	19-23	25-27	3-7	8-13	14-18	19-23	25-27
		Plantation Age Class (Years)									
F_2		Cumulative Rust Infection (%)					Cumulative Rust Mortality (%)				
East Thunder	1	43.7	81.7	86.5			2.4	20.6	38.9		
Pick & Pan	1	11.0	19.2	50.7			0.0	2.7	11.0		
Remas	1	29.3	53.5	61.6			17.2	27.3	28.3		
Big Foxy	2	7.8	26.2	32.0			1.9	12.6	16.5		
Blue Creek	2	7.1	25.3	41.4			1.0	8.1	12.1		
Contrary Creek	2	0.0	0.0	9.0			0.0	0.0	0.0		
Happy Blue	2	29.6	42.9	52.0			17.3	27.6	32.7		
Lost Cat	2	23.2	42.0	51.8			7.1	25.0	31.3		
Lost Jungle	2	14.3	26.0	35.1			0.0	15.6	19.5		
POL 92 - A	3	0.0	8.0	22.7	36.4		0.0	1.1	4.5	6.8	
Uleda Creek	3	0.0	11.4	29.8	57.0		0.0	0.9	7.9	16.7	
Varnum 11	6	1.9	23.6	29.2	50.0		0.9	3.8	9.4	18.9	
Varnum 23b	7	2.7	40.5	51.4	70.3		0.9	11.7	33.3	36.0	
Copper-Gimlet 1	9		39.1	49.4	67.8	81.0		14.9	30.5	37.9	39.7
Copper-Gimlet 2	9		13.1	45.9	45.9	55.7		9.8	16.4	18.0	18.0
Keokee Creek	10		33.6	40.4	48.4	60.5		25.1	30.9	33.6	37.2
Paradise Valley	10		0.9	0.9	4.5	6.3		0.9	0.9	0.9	0.9
Waters Creek	10		49.3	75.7	83.8	83.8		31.6	43.4	55.1	63.2
All the Way	11		0.0	0.0	5.3	6.3		0.0	0.0	0.0	0.0
Copper-Gimlet 21	11		35.4	45.7	47.0	51.2		17.1	31.1	34.8	39.0
Average		13.1	28.6	40.6	46.9	49.2	3.7	12.8	19.9	23.5	28.3
Change			15.5	12.0	6.3	2.3		9.1	7.1	3.6	4.8
NATURAL[1]											
Contrary Creek	2	0.0	0.0	7.7			0.0	0.0	0.0		
POL 92 - A	3	0.0	29.5	56.8	73.9		0.0	9.1	21.6	27.3	
Varnum 11	6	0.0	66.7	75.0	75.0		0.0	8.3	50.0	50.0	
Varnum 23b	7	3.5	64.9	64.9	68.4		3.5	38.6	49.1	49.1	
Copper-Gimlet 1	9		37.9	72.4	82.8	86.2		17.2	27.6	62.1	65.5
Copper-Gimlet 2	9		37.5	87.5	87.5	87.5		37.5	75.0	87.5	87.5
Copper-Gimlet 21	11		17.2	59.5	67.2	75.9		7.8	44.8	50.9	55.2
Average		0.9	36.2	60.5	75.8	83.2	0.9	16.9	38.3	54.5	69.4
Change			35.4	24.3	15.3	7.4		16.1	21.4	16.2	14.9

[1] Sites with 10 or more natural white pine

Determination of the timing of infection events through periodic monitoring is challenging, and the several-year lag time between needle infection and the appearance of identifiable cankers contributes to this challenge. Some plantations had large increases in incidence of WPBR in all stock types between the 1995 and 2000 measurements. At least some of the increase in incidence from 1995–2000 may be due to a widespread "wave year" of infection, a period of highly favorable environmental conditions for successful WPBR infection thought to have

occurred in 1995-1996 (Schwandt et al. 2013b). However, not all plantations had higher infection levels during this period, so favorable conditions may not have been universally present or other factors may have played a larger role in the infection process.

Mortality from White Pine Blister Rust

After 16 years of monitoring, mortality levels for F_2 stock were lower than F_1 stock or natural regeneration. In 1995, the average mortality of the F_2 plantations was 5.6% (Table 2). Ten of the 18 F_2 plantations had no mortality, while WPBR-caused mortality in the other eight F_2 plantations ranged from 0.9% to 31.6%. Mortality was highest in the oldest plantations; only two plantations less than nine years old (Varnum 11 and Varnum 23b) had any WPBR-caused mortality. In 1995, 89.2% of all 2,060 F_2 trees were still alive (Table 5). Of the 10.8% of F_2 that were dead, WPBR had killed 73%, root diseases 7%, and other causes (including bear damage, inadvertent cutting, insects, and unknown causes) 20% (Table 5).

By 2000, the average WPBR-caused mortality for all 20 F_2 plantations increased to 10.9%, and 13.7% of all F_2 stock had been killed by WPBR (Table 2). Only three of the ten plantations with no WPBR-caused mortality in 1995 still had no WPBR-caused mortality by 2000. Two plantations (Remas and Happy Blue) had no observed WPBR infections in 1995 but experienced over 17% mortality by 2000. Seventy-five percent of the F_2 were alive, and WPBR accounted for 67% of the mortality that had occurred. Root diseases caused 13% of the mortality, and other causes were responsible for the remaining 20% (Table 5).

Table 5. Percent western white pine survival and cause of death by stock type and measurement year.

	F_2[1]					F_1					Natural				
			Cause of death					Cause of death					Cause of death		
Year	Alive	Missing	Blister Rust	Root Disease	Other	Alive	Missing	Blister Rust	Root Disease	Other	Alive	Missing	Blister Rust	Root Disease	Other
			%					%					%		
1995	89.2	0.0	7.9	0.8	2.1	72.7	0.0	26.5	0.0	0.8	84.1	0.0	14.8	0.0	1.1
2000	75.0	4.6	13.7	2.6	4.1	38.4	0.8	58.0	1.6	1.2	45.9	2.2	48.1	1.5	2.4
2006	62.6	3.4	21.6	5.4	6.9	20.0	0.8	72.2	3.3	3.7	27.5	3.2	57.9	3.2	8.2
2011	52.9	4.7	26.3	7.0	9.1	15.1	1.2	75.5	4.5	3.7	21.0	9.7	60.5	3.9	4.9

[1] In 1995 F_2 N=2060, in all other years F_2 N=2259, F_1 N=245 in all years, and N=466 for Naturals throughout the study.

By 2006, the average F_2 plantation WPBR-caused mortality increased to 18.7% (range 0% to 55.1%), and 21.6% of F_2 stock had been killed by WPBR (Table 2). Survival among the F_2 stock dropped to 62.6% (Table 5). As a proportion of the cumulative mortality in 2006, 64% was attributed to WPBR, 16% to root diseases, and 20% to other causes.

By 2011, all but two of the F_2 plantations had experienced some mortality due to WPBR. WPBR-caused mortality averaged 23.3% across the 20 F_2 plantations (with a range of 0% to

63.2%) and 26.3% of all F_2 stock had been killed by WPBR (Table 2). At plantation ages ranging from 17–27, survival of the F_2 stock declined to 52.9% (Table 5). WPBR was responsible for 62% of the cumulative mortality, root diseases 17%, and other causes 21%. Over the 16-year monitoring period the average annual WPBR-related mortality rate in the F_2 plantations was 1.1%, slightly less than half that of the average annual infection rate although this varied by plantation (Table 2). Half of the F_2 plantations had average annual mortality rates of less than 1.0%, and most of these had mortality levels less than 50% of the infection levels and infection levels less than 50% in 2006.

WPBR-caused mortality in the F_1 stock increased from 26.5% in 1995 to 75.5% in 2011, while rust-related mortality in natural regeneration in the same two plantations increased from 34.8% in 1995 to 94.1% in 2011 (Table 2). Only 21% of all the natural regeneration (from both the F_2 and F_1 plantations) was still alive in 2011 (Table 5); WPBR accounted for 87% of the mortality, root diseases 6%, and other causes 7%. In 1995, 6.7% of all natural regeneration in F_2 plantations had been killed by WPBR (average among the seven F_2 plantations was 9.4%) (Table 2); by 2011, 46.8% of naturals in F_2 plantations had been killed by WPBR (plantation average 47.8%). By 2011, only two of the nine F_1 and F_2 plantations with more than ten monitored naturals had WPBR-caused mortality below 30% and the remaining seven plantations had WPBR-caused mortality in excess of 49%.

The cumulative WPBR-caused mortality for all stock types appears to begin to level off after the 2006 measurement (Figure 3). However, when broken down by plantation age class, the average cumulative WPBR-caused mortality does not appear to decline with plantation age (Figure 4, Table 4). The average cumulative F_2 mortality is increasing at a much slower pace than the average for the natural regeneration (Table 4).

Mortality trends for the nine oldest F_2 plantations are highly variable (Figure 6) and do not always follow the incidence trends (Figure 5). For example, the percent infection in several plantations increases but mortality appears to level off, while just the opposite is observed in other plantations. Similar inconsistencies are also observed between measurements. This makes it difficult to determine the trajectory of a stand based on the relatively short time interval of 16 years.

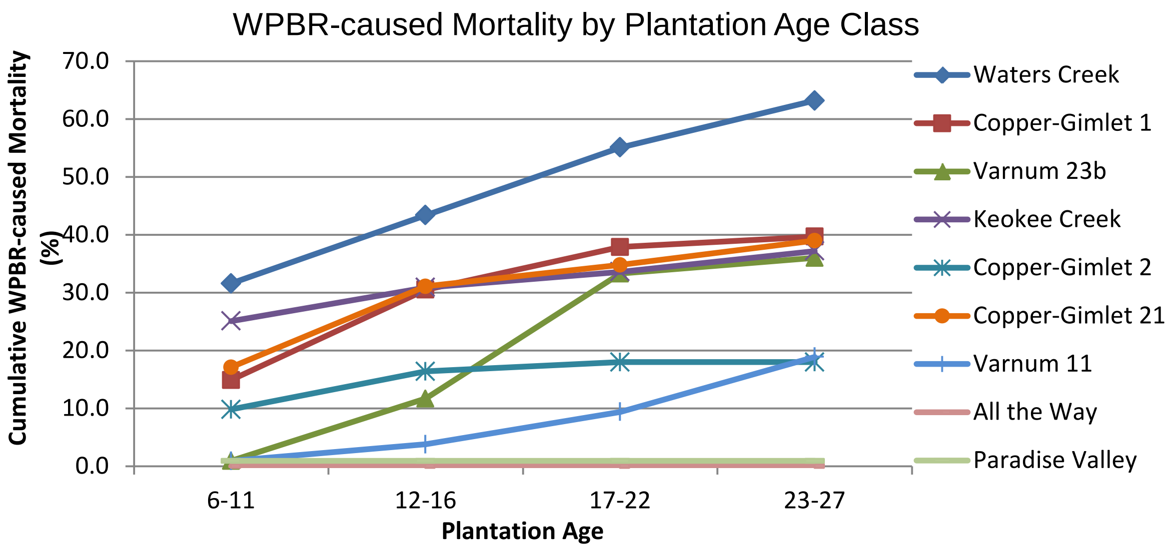

Figure 6. Mortality trends in the nine oldest F_2 plantations over time.

A critical question in management of F_2 western white pine is how long trees live once they become infected by WPBR. To address this, the fates of trees that were infected by a given measurement year were tracked over time. Of the 282 F_2 western white pines that were WPBR-infected, including both live and dead trees, by the 1995 measurement; 57% had been killed by 1995; 82% by 2000; 89% by 2006; and by the last measurement in 2011, 92% had been killed by WPBR. Of the 23 trees not killed by WPBR over the 16-year monitoring period, nine were alive but infected by WPBR (four of which had bole cankers), seven were alive with no apparent WPBR infections, four had been killed by root disease, two died from unknown causes, and one could not be located. Three hundred sixty-four F_2 western white pines became infected between the 1995 and 2000 measurements. Of those, 22% had been killed by WPBR by 2000, 59% by 2006, and 72% by 2011. Of the remaining F_2 stock infected between the 1995 and 2000 measurements, in 2011 13% were still alive and infected by WPBR (72% of which had bole infections), 7% were alive and no longer infected with WPBR, 2% died from root disease, 4% were dead from other causes, and 2% could not be located. An additional 282 F_2 became infected between the 2000 and 2006 measurements. By 2011, 23% had been killed by WPBR, 61% were alive with WPBR cankers (53% of which had bole cankers), 6% had died from root disease, 3% died from other causes, 5% were alive with no apparent WPBR infections, and 2% were missing.

The assumption is often made that much F_2 stock, even if infected by *C. ribicola*, will live long enough due to its genetic resistance to attain merchantable size. Our data, however, indicate that the vast majority of infected trees die within 10-15 years. In some cases WPBR branch cankers become inactivated as branches are shaded out or shed between measurement periods; however, that appears to happen in a very small percent of our sampled trees. These results support

findings by Schwandt et al. (2013b) and further validate previous results from this monitoring study (Kearns et al. 2012).

White Pine Blister Rust Severity

Severity of WPBR infection may have an important influence on future mortality. F_2 western white pine had a lower percentage of lethal cankers and a higher percentage of prunable cankers than either the F_1 or the naturals in these plantations. Thirty-four percent of living and infected F_2 had prunable cankers, and pruning in the near future has the potential to prolong the lives of these trees by removing existing infections before they reach the bole and girdle the tree. It is important to note that not all plantations would benefit equally from pruning. The percentage of trees with prunable cankers in individual plantations varied from 0% to 63%; plantations with currently low WPBR infection levels may not benefit substantially from pruning. Ten percent of the infected F_2 trees had cankers beyond 24 inches from the bole and were considered to be safe. However, since these trees were infected once they are susceptible to future infection, which could be lethal, and so they could also benefit from pruning (Schnepf and Schwandt 2006, Schwandt et al. 2013a).

Pruning has been shown to decrease WPBR-caused mortality of natural or “woods-run” western white pine by nearly 50% over the subsequent 40 years (Schwandt and Marsden 2000, Schwandt and Ferguson 2003, Schwandt and Ferguson in prep). Unfortunately, we do not have long-term data from pruned and (or) thinned F_2 plantations, but expect increased survival equal to or even better than the results from natural stock. While pruning in the near future has the potential to save 34% of the infected F_2 stock in these plantations, pruning at an earlier date to remove cankers before they became lethal may have saved even more trees. As a result, mortality on some of the more highly infected sites may have been reduced to a level that meets economic and ecological thresholds for western white pine stocking (Schwandt et al. 2013a, Schnepf and Schwandt 2006).

Site Factors and Hazard Rating

In order to effectively manage western white pine stands in the Inland Northwest where WPBR infection and mortality levels vary widely between sites, hazard rating to determine the potential impacts from WPBR is crucial. One example is a preliminary expert hazard rating system developed by Rust (1988) based on habitat type and potential *Ribes* density based on site preparation method, slope, aspect, and the amount of disturbance to the duff layer. Hagle et al. (1989) recommended using a rust index based on a computer simulation model created by McDonald et al. (1981) that measured the number of cankers per thousand needles per year accumulated over a minimum of ten years as the best basis for determining future hazard for the regeneration of western white pine stands. Hunt (1983) used slope percent, canker growth rate and mortality, and stem density to rate the hazard to white pines in British Columbia. Trees at the greatest hazard for damage were those that were open grown on slopes, while those growing

in dense stands in flat areas had the lowest hazard. Proximity to *Ribes*, microsite effects, and canker growth and mortality rates resulted in slight variations in hazard (Hunt 1983).

Some of the 22 plantations monitored in this study appear to be in very low rust hazard sites. For example, it appears that Contrary Creek may be in a low hazard area since the incidence of WPBR in natural regeneration in this plantation is only 7.7% (Table 2) while the average infection of natural regeneration in the other six F_2 plantations is 10 times this level (77.8%). It also appears that several plantations are in high hazard areas. For example, the incidence of WPBR in the two F_1 plantations averaged nearly 95%, and East Thunder, which was one of the youngest F_2 plantations, quickly became the most severely infected (86.5%).

Muller (2002) evaluated WPBR impacts on 41 F_2 western white pine plantations in northern Idaho that were 8–21 years old, including some from this study, to try to correlate WPBR infection rates with a variety of site conditions. Infection levels on Muller's sites ranged from 2% to 95% and averaged 36%. Muller found that elevation and percent slope were the two best predictors of annual rate of infection (AIR). He used these site data to develop an equation to estimate the annual infection rate (eAIR in contrast to actual AIR (aAIR)). Using Muller's model, the eAIRs for the 20 F_2 plantations in this study were calculated and compared with the actual AIRs (Table 6). The average eAIR for the 20 F_2 plantations in this study was 2.33, which is very similar to the actual average aAIR of 2.38. However, in a site-by-site comparison, the eAIR estimates calculated with Muller's equation were usually very poor predictors of the actual AIRs (Table 6).

Rust hazard can also be estimated by measuring within stand *Ribes* populations, but this method was not considered as effective as the rust index (Hagle et al. 1989). Muller (2002) reported that *Ribes* density was significantly correlated with WPBR incidence on most of his study sites. Schwandt and Ferguson (2003) reported 40% WPBR incidence in plots with *Ribes* and 22% incidence on plots without *Ribes* present. Hagle et al. (1989) indicated that *Ribes* counts between 25 and 100 per acre present a moderate risk of WPBR infection, while sites with *Ribes* counts over 100 per acre are high risk.

There was a positive though weak correlation ($r = 0.33$) between WPBR incidence and *Ribes* densities on the 0.05-acre monitoring plots in the 20 F_2 plantations in this study (Table 6). Average incidence of infection among the three F_2 plantations with fewer than 25 *Ribes* bushes per acre in 2004 was 24.9%. It increased to 36.5% in the four plantations with *Ribes* densities between 25-100 bushes per acre, then to 57.4% in the six plantations with *Ribes* densities between 100–1000 bushes per acre, and finally to 64.7% in the six plantations with >1000 *Ribes* bushes per acre. Of the 12 F_2 plantations with *Ribes* densities above 100 bushes per acre, only one plantation (Big Foxy) had an infection level less than 50% (32%); the others ranged from 50% to 87%.

Table 6. Site attributes for 20 F_2 western white pine plantations sorted by actual annual infection rate (aAIR).

Plantation	Actual aAIR[1]	Muller's eAIR[2]	2011 Infection	2011 Mortality	Ribes/ac. 2004	Elev . ft.	Slope %	Aspect	Site Preparation
			Percent						
All the Way	0.23	1.9	6.3	0.0	0	4200	0	N	Burned
Paradise Valley	0.24	0.2	6.3	0.9	0	2280	0	Flat	Piled/burned
Contrary Creek	0.50	1.1	9.0	0.0	75	3240	10	W	Hoe piled
Big Foxy	1.78	2.9	32.0	16.5	550	4200	25	N	Burned
Copper-Gimlet 21	1.90	2.3	51.2	39.0	107	2800	60	NE	Burned
POL 92 - A	1.92	1.7	36.4	6.8	10	3600	15	W	Burned
Lost Jungle	1.95	2.0	35.1	19.5	83	3400	30	W	Burned
Copper-Gimlet 2	2.23	3.5	55.7	18.0	1367	4000	45	NE	Burned
Varnum 11	2.27	2.0	50.0	18.9	160	3400	30	NE	Burned
Blue Creek	2.30	0.6	41.4	12.1	33	2840	5	SW	Spring burn
Keokee Creek	2.33	1.8	60.5	37.2	46	3700	15	SW	Burned
Lost Cat	2.88	4.2	51.8	31.3	1800	4200	50	NE	Burned
Happy Blue	2.89	3.5	52.0	32.7	3140	4400	30	NE	Not burned
Pick & Pan Creek	2.98	0.9	50.7	11.0	20	3200	5	SE	Burned
Uleda Creek	3.00	3.7	57.0	16.7	360	4400	35	NE	Burned
Varnum 23b	3.06	1.6	70.3	36.0	108	2800	40	NW	Burned
Copper-Gimlet 1	3.24	3.2	81.0	39.7	1208	3800	45	NE	Burned
Waters Creek	3.22	2.8	83.8	63.2	200	4420	15	S	Burned
Remas	3.62	4.1	61.6	28.3	2317	4000	55	NE	Burned
East Thunder	5.09	2.7	86.5	38.9	1162	4200	20	NW	
Average for F_2 plantations	2.38	2.33							

[1] Annual infection rate calculated from 2011 data in Table 2.

[2] Estimated annual infection rate calculated from an equation developed by Muller(2002).

Data from this study suggest that sites with less than about 20 *Ribes* per acre should also have relatively low WPBR infection and mortality rates. Even with plantation ages of 26–27, the two plantations with no recorded *Ribes* presence had the lowest WPBR incidence. However, these relationships are based on a relatively small number of trees on a small number of sites. More monitoring data from many more sites are needed before variation in *Ribes* counts can be developed into a reliable indicator of rust hazard. While *Ribes* density appears to be related to WPBR intensity in some plantations, it is not consistent enough to be used on all sites.

This work and earlier efforts by many others clearly show that developing a reliable hazard rating tool is very complicated. A closer comparison of site characteristics and weather data between plantations with high and low AIR values may help clarify these relationships. Additional periodic monitoring may also reveal longer-term trends that are not currently apparent.

SUMMARY and MANAGEMENT IMPLICATIONS

This long-term monitoring project has provided important data on WPBR incidence and mortality in young, rust-resistant western white pine in northern Idaho. The following results can be applied to current management of western white pine and guide future efforts to further improve its utilization:

- F_2 stock continues to substantially outperform both F_1 stock and natural regeneration in the presence of WPBR but with wide variation in incidence and resultant mortality. The belief, based on early nursery trials (Hoff et al. 1973), that 66% of F_2 western white pine would remain canker-free has not held true in 80% of F_2 plantations in this study.
- There was initial hope that F_2 stock might be able to tolerate or slow down WPBR canker growth, as early measurements of these plantations found mortality was relatively low in infected trees (Kearns et al. 2012). The 2011 results indicate that mortality simply lags behind infection by several years, and once young trees become infected, they have a high probability of dying in 10–15 years. This supports the recommendation of "ghosting" (leaving alone) severely infected trees when pruning or thinning to 1) provide temporary shade that will help minimize sunscald and *Ribes* growth, and 2) provide cost savings from not cutting trees that will die within a few years (Schnepf and Schwandt 2006, Schwandt et al. 2013a).
- The three plantations with the lowest infection levels suggest that mortality may remain low in plantations that are more than 15 years old with less than 10% infection. Most plantations with infection levels greater than 40% percent by age 15 had highly variable trajectories and suffered at least 35% mortality within the next 10-15 years.
- It has been suggested that incidence and mortality levels might level off if WPBR was removing the most susceptible trees (Kearns et al. 2012), but after 16 years of monitoring, both incidence and mortality due to WPBR continue to increase, although the rate of increase varies widely between plantations.
- F_2 plantations on sites where the annual mortality rate remains at or below about one percent should have half of the western white pine survive to a rotation age of 50 or 60. These losses might be mitigated by increasing initial planting density and/or pruning. However, these estimates do not include mortality from the other causes, which must be considered when making planting decisions.
- While *Ribes* density appears to be related to WPBR intensity in some plantations, it is not consistent enough to be used on all sites.
- While developing a reliable hazard rating tool will be very complex, forest managers must be able to accurately predict WPBR infection levels and long-term survival on a site-by-site basis. If this can be done, managers can focus management investments and activities on sites with the best probability of success. To accomplish this, the factors that determine (or predict) rust hazard must be identified so that long-term estimates of rust mortality can be

developed. Lack of a reliable hazard-rating system remains a major roadblock to efficient utilization of rust-resistant western white pine.

- WPBR can increase dramatically over short periods. Therefore, periodic monitoring of plantations for WPBR levels is critical for bringing plantations through to an economic rotation. We know that timely pruning can increase survival in some plantations; many lethal cankers could have been safely pruned a few years ago thereby improving survival of a larger proportion of trees.

The key to restoration of western white pine in the Northern Rockies is an intensive program of planting and managing, primarily through pruning, rust-resistant western white pine. Over 250,000 acres have been planted to-date. In the last 15–20 years, however, planting has dropped by approximately 70%; 13,000 acres per year to less than 4,000; even though there is surplus seed in storage (Schwandt et al. 2013a). At current planting levels of 2,000–4,000 acres per year it will take 250–500 years to reforest just 20% of the five million acres of prime western white pine habitat in the Inland Northwest.

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REFERENCES CITED

Bingham, R.T. 1983. Blister rust resistant western white pine for the Inland Empire: the story of the first 25 years of the research and development program. General Technical Report INT-146. USDA Forest Service, Intermountain Forest and Range Experiment Station; Ogden, Utah. 45 p.

Bingham, R.T.; Squillace, A.E.; and Duffield, J.W. 1953. Breeding blister-rust-resistant western white pine. Journal of Forestry 51: 163-168.

Bingham, R.T.; Hanover, J.W.; Hartman, H.J.; and Larson, Q.W. 1963. Western white pine experimental seed orchard established. Journal of Forestry 61: 300-301.

Bingham, R.T.; Hoff, R.J.; and McDonald, G.I. 1973. Breeding blister rust resistant western white pine. VI. First results from field testing of resistant planting stock. Research Note INT-179. USDA Forest Service, Intermountain Forest and Range Experiment Station; Ogden, Utah. 12 p.

Byler, J.W.; and Hagle, S.K. 2000. Succession functions of pathogens and insects: ecoregion sections M332a and M333d in northern Idaho and western Montana: Summary. FHP Report No. 00-09. USDA Forest Service, Northern Region, State and Private Forestry, Forest Health Protection; Missoula, Montana. 37 p.

Eckert, A.I. 2007. Field classification of white pine blister rust stem cankers on resistant western white pine in northern Idaho and determination of respective tissue damage through tree ring analysis. M.Sc. Thesis. Oregon State University; Corvallis, Oregon. 78 p.

Fins, L.; Byler, J.; Ferguson, D.; Harvey, A.; Mahalovich, M.F.; McDonald, G.; Miller, D.; Schwandt, J.; and Zack, A. 2001. Return of the Giants. Station Bulletin 72. University of Idaho; Moscow, Idaho. 20 p.

Hagle, S.K.; McDonald, G.I.; and Norby, E.A. 1989. White pine blister rust in northern Idaho and western Montana: alternatives for integrated management. General Technical Report INT-261. USDA Forest Service, Intermountain Research Station; Ogden, Utah. 35 p.

Harvey, A.E.; Byler, J.W.; McDonald, G.I.; Neuenschwander, L.F.; and Tonn, J.R. 2008. Death of an ecosystem: perspectives on western white pine ecosystems of North America at the end of the twentieth century. General Technical Report RMRS-208. USDA Forest Service, Rocky Mountain Research Station; Fort Collins, Colorado. 10 p.

Hoff, R.J.; McDonald, G.I.; and Bingham, R.T. 1973. Resistance to *Cronartium ribicola* in *Pinus monticola*: structure and gain of resistance in the second generation. Research Note INT-178. USDA Forest Service, Intermountain Forest and Range Experiment Station; Ogden, Utah. 8 p.

Hunt, R.S. 1983. White pine blister rust in British Columbia. II. Can stands be hazard rated? Forestry Chronicle 59(1): 30-33.

Kearns, H.S.J.; Ferguson, B.A.; and Schwandt, J.W. 2012. Performance of rust-resistant western white pine in operational plantations in northern Idaho: 1995-2006. FHP Report No. 12-03. USDA Forest Service, Northern Region, State and Private Forestry, Forest Health Protection; Missoula, Montana. 27 p.

Ketcham, D.E.; Wellner, C.A.; and Evans, S.S., Jr. 1968. Western white pine management programs realigned on northern Rocky Mountain National Forests. Journal of Forestry 66: 329-332.

Lachmund, H.G. 1926. Studies of white pine blister rust in the West. Journal of Forestry 24: 874-884.

Lupo, P. 2004. Stability and expectations of blister rust resistance traits in F_2 western white pine. M.Sc. Thesis. University of Idaho; Moscow, Idaho. 131 p.

Mahalovich, M.F. 2010. U.S.A. Inland Northwest Western White Pine Breeding and Restoration Program: history, current and future directions. Pages 50-74 *in*: Proceedings of the 3rd Western White Pine Management Conference; June 17-18, 2008; Vernon, B.C. Cleary, M., ed. British Columbia Ministry of Forests and Range; Kamloops, British Columbia. 116 p.

Maloy, O.C. 1997. White pine blister rust control in North America: a case history. Annual Review of Phytopathology 35: 87-109.

Mathiasen, R.; and Schwandt, J. 1993. Monitoring genetically improved western white pine plantations for blister rust infection in northern Idaho: Idaho state and Forest Service lands: establishment and preliminary results: 1991-92. Report No. IDL 93-2. Idaho Department of Lands; Coeur d'Alene, Idaho. 10 p.

Matthews, D.N.; and Hutchison, S.B. 1948. Development of a blister rust control policy for the national forests in the Inland Empire. Station Paper No. 16. USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station; Missoula, Montana. 116 p.

McDonald, G.I.; Hoff, R.J.; and Wykoff, W.R. 1981. Computer simulation of white pine blister rust epidemics. I. Model formulation. Research Paper INT-258. USDA Forest Service, Intermountain Forest and Range Experiment Station; Ogden, Utah. 136 p.

Mielke, J.L. 1943. White pine blister rust in western North America. Bulletin No. 52. Yale University, School of Forestry; New Haven, Connecticut. 155 p.

Molnar, A.C.; and McMinn, R.G. 1960. The origin of basal scars in the British Columbia interior white pine type. Forestry Chronicle 36(1): 50-60.

Moss, V.D.; and Wellner, C.A. 1953. Aiding blister rust control by silvicultural measures in the western white pine type. Circular No. 919. U.S. Department of Agriculture; Washington, D.C. 32 p.

Muller, J.J. 2002. Environmental variables associated with field performance of blister rust resistant F_2 western white pine in the Inland Empire. M.Sc. Thesis. University of Idaho; Moscow, Idaho. 65 p.

Neuenschwander, L.F.; Byler, J.W.; Harvey, A.E.; McDonald, G.I.; Ortiz, D.S.; Osborne, H.L.; Snyder, G.C.; and Zack, A. 1999. White pine in the American West: a vanishing species - can we save it? General Technical Report RMRS-GTR-35. USDA Forest Service, Rocky Mountain Research Station; Moscow, ID. 21 p.

Rust, M. 1988. White pine blister rust hazard rating: an expert systems approach. AI Applications 2: 47-50.

Samman, S.; Schwandt, J.W.; and Wilson, J.L. 2003. Managing for healthy white pine ecosystems in the United States to reduce the impacts of white pine blister rust. Report R1-03-118. USDA Forest Service; Missoula, Montana. 10 p.

Schnepf, C.C.; and Schwandt, J.W. 2006. Pruning western white pine: a vital tool for species restoration. Pacific Northwest Extension Publication PNW-584. University of Idaho Extension, Oregon State University Extension Service, and Washington State University Cooperative Extension, in cooperation with the U.S. Department of Agriculture; Moscow, Idaho. 62 p.

Schwandt, J.; and Ferguson, B. 2003. Performance of F_2 western white pine plantations in northern Idaho. Pages 100-105 *in*: Proceedings of the Fiftieth Western International Forest Disease Work Conference; October 7-11, 2002; Powell River, British Columbia. Stone, J.; and Maffei, H., comps. USDA Forest Service, Central Oregon Forest Insect and Disease Service Center; Bend, Oregon. 181 p.

Schwandt, J.W.; and Marsden, M.A. 2000. Pruning and thinning effects after 30 years in northern Idaho white pine stands. Proceedings of the Western International Forest Disease Work Conference 48: 23-29.

Schwandt, J.W.; Kearns, H.S.J.; and Byler, J.W. 2013a. White pine blister rust: general ecology and management. FHP Report No. 23-07. USDA Forest Service, Northern Region, State and Private Forestry, Forest Health Protection; Missoula, Montana. 25 p.

Schwandt, J.W.; Kearns, H.S.J.; Marsden, M.A.; and Byler, J.W. 2013b. White pine blister rust canker expansion on improved western white pine in northern Idaho: implications for the management of rust-resistant stock. FHP Report No. 13-03. USDA Forest Service, Northern Region, State and Private Forestry, Forest Health Protection; Missoula, Montana. 12 p.

Smith, J.K.; and Fischer, W.C. 1997. Fire ecology of the forest habitat types of northern Idaho. General Technical Report INT-363. USDA Forest Service, Intermountain Research Station; Ogden, Utah. 142 p.

Steinhoff, R.J. 1971. Field levels of infection of progenies of western white pine selected for blister rust resistance. Research Note INT-146. USDA Forest Service, Intermountain Forest and Range Experiment Station; Ogden, Utah. 4 p.